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INVESTIGATIONS OF CEMENTED AND DETACHABLE JOINTS OF FIBER REINFORCED PLASTICS

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INVESTIGATIONS OF CEMENTED AND DETACHABLE JOINTS OF FIBER REINFORCED PLASTICS[1]

W. Althof and J. Mueller

ABSTRACT: Laminated structures of plastics reinforced with carbon and boron fibers and containing bolt holes were tested for strength under different conditions of fiber orientation, hole diameter, and hole spacing from the edges. Laminates with fiber orientations in 0° and ±45° reach a relatively high bolt hole strength even with relatively small end spacing and should be preferred for aircraft construction.

A large number of practical adhesives are suitable for bonding boron fiber reinforced plastic laminates to themselves or to steel and titanium sheeting. Deformable high strength adhesives gave the highest bond strengths.

In the utilization of fiber reinforced plastics in structural members, the question comes up in particular about the suitable strengthening because of the anisotropy of the material. For this reason some experiments were carried out on plastics reinforced with boron filaments and with carbon filaments. The behavior of bolted and cemented joints on multiple laminates with variable fiber orientation is reported in the following. /911*

The practical utilization of fiber reinforced materials for structural members requires not only a knowledge of the mechanical properties of the material, but also the experiences and knowledge on the formation of joining elements, such as screw, rivet and adhesive joints.

The first step in the determination of the strength behavior of joining elements of plastics reinforced with boron filaments and carbon filaments (BFK and KFK, respectively) was made with bolt hole wall experiments on symmetrically loaded bolted joints and with adhesion experiments.

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[1]Lecture at the annual public meeting of the Study Group of Reinforced Plastics, 6-9 October 1970 at Freudenstadt.

*Numbers in the margin indicate pagination in the foreign text.

Experimental Materials

As may be seen from Table 1, prepregs were used for the preparation of samples both for the bolt hole, as well as the adhesive experiments; these were either prepared in our own laboratory (DFVLR-BFK) or were ordered commercially (Scotchply-BFK, FH-KFK). Table 1 also gives details about the preparation of prepreg and laminate, as well as the designation of the reinforcing material and plastic matrix. The principle of the prepreg preparation was described previously. [1].

Bolt Hole Experiments with Carbon Filament Reinforced Plastics

The aim of the bolt hole investigations as for conventional materials, was to optimize the possible forms of failure, i.e., bolt hole failure, shear failure, tension failure, as shown in Figure 1, by the choice of end spacings and side spacing so that the most coincident failure possible would occur in the endangered places.

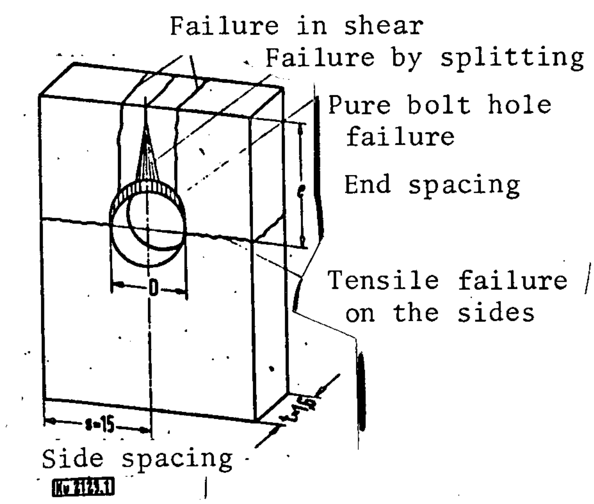

Figure 1. Forms of Failure of Bolted Joints. Dimensions in mm.

Experimental Arrangement

The end spacing e and the hole diameter D were varied for the experiments, while the width $2s$ = 30 mm and the thickness t = 1.6 mm were kept constant, as shown for the sample in Figure 1.

Samples with ratios of /912
end spacing to bolt diameter e/D = 1, 2, 3, 4, 5 were tested, as well as bolt diameters of D = 6, 8, and 10 mm.

TABLE 1. LAMINATES USED, DESIGNATIONS AND CONDITIONS OF WORKUP. BFK = = BORON FILAMENT REINFORCED PLASTICS; KFK = CARBON FILAMENT REINFORCED PLASTICS.

Laminate designation		DFVLR-BFK	Scotchply-BFK	FH-KFK
Prepreg designation		--	Scotchply SP 272	Carboform
Prepreg manufacturer		German Research & Testing Lab for Aeronautics and Astronautics	3M-Comp. St. Paul, Minn, U. S.A.	Fothergill and Harvey, Littleborough, England
Resin & mixing ration		Ruetapax L02 (Epoxide) 100 parts (wt.). Hardener SL (polyaminoamide) 44 parts (wt.)	PR-279 (Epoxide)	LY 558 (Novolak-Epoxide) + HT 973 BF_3-complex
Resin manufacturer		Ruetgers Works, Frankfurt	3M-Comp.	Ciba, Basel/ /Switzerland
Temp.(°C)		+80	+165	+170
Cure	Time (hrs)	2	1	1
	Pressure (kp/cm^2)	1	7	7
Post-cure	Temp (°C)	+100	+175	+170
	Time (hrs)	3	4-6	2
Orientation of the individual layers* (degrees)		Inside hole: each 2x ± 45 8 x 0. each 2x ± ± 45 Adhesion: 0	Adhesion: 3 x 0 2 x 90 3 x 0	Inside of hole: a) 16 x 0; b) each 8x ±45; c) each 2x ± 45; 8 x 0 each 2x ± 45

*Angle between filament and load direction, filament contact for KFK about 60 Vol. %.

Sixteen-ply laminates were investigated with three different fiber orientations in 0°, in ±45° as well as in 0 and ±45° direction (8 layers with 0° and each 4 layers with ±45° fiber reinforcement) in the direction of loading. In order to avoid unsymmetrical deformation, the last two laminates were built up in symmetry with the middle plane. For the samples with fiber orientation of 0 and ±45°, the layers oriented in the 0° direction were placed in the middle and the layers oriented in the ±45° direction were placed towards the surface.

The loading arrangement corresponds to the customary design for bolt hole experiments for symmetrical loading.

Results of Experiments

Two safe load bearing capacity limits can be principally differentiated:

1) Separation failure as a result of reaching a tensile break.

2) Safe load bearing capacity limits as a result of surpassing a certain hole expansion. This deformation ε_l is thereby related to the bolt diameter

$$\varepsilon_l = \frac{\Delta D}{D} \cdot 100\% .$$

It was shown for the bolt hole experiments that the load-hole expansion curves have a linear course up to a certain point in the graph for all laminates with the various fiber orientations. The lower linearity limits of these curves are at ε_l = 0.5% for all fiber orientations; the upper linearity limits lie at 0.6 to 0.9% relative hole expansion according to the type of reinforcement. It therefore seemed logical to define a relative hole expansion of ε_l = 0.5% at elastic deformation limit, in analogy with the known material proportionality limit.

Laminates with Reinforcements in the 0° Direction:

The mean bolt hole compression stresses and shear stresses for the relative hole expansion of ε_l = 0.5% are plotted in Figure 2 in relation to e/D with D as parameter.

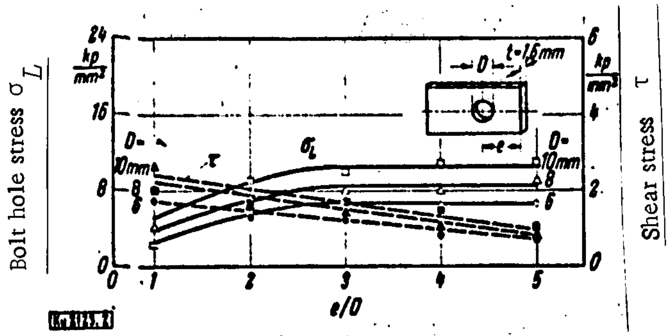

Figure 2. Fiber Orientation 0°.

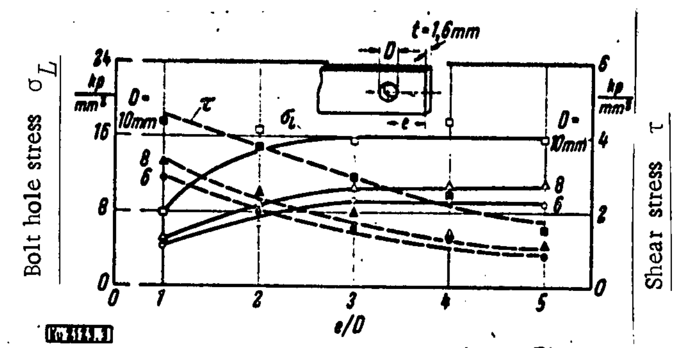

Figure 3. Fiber Orientation ±45°.

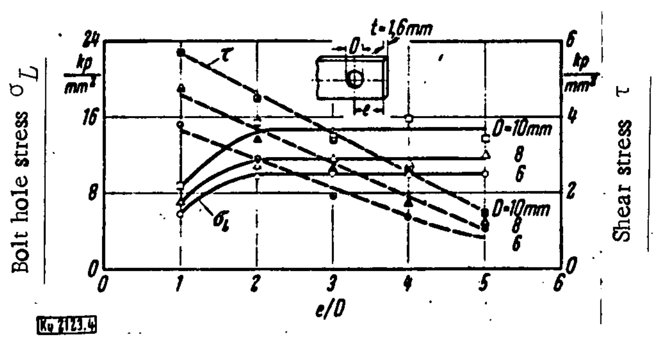

Figure 4. Fiber Orientation 0 ± 45°.

Figures 2 to 4. Bolt Hole Compression Stress σ_L and Shear Stress τ of Bolted Joints in Carbon Fiber Reinforced Plastics (KFK) as Function of e/D and D for the Relative Hole Expansion $\varepsilon_l = 0.5\%$

$\sigma_L = P/(D\ t)$; $\tau = P/(2\ t\ [e - D/4])$.

The mean shear stresses were calculated for these under the assumption that they are activated by load P in a plane at a spacing of 0.40 from the center of the hole parallel to sample side edges [2].

The curves for the bolt hole stresses σ_L run asymptotically and reach a limiting value at $e/D \approx 3.2$. The shear stresses τ fall off continuously with increasing e/D.

The maximum bolt hole compression stresses amount to $\sigma_L = 7.1$ for a relative hole expansion $\varepsilon_l = 0.5\%$; 9.2 and 10.8 kp/mm^2 for a bolt diameter $D = 6$, 8 and 10 mm. A distinct improvement of these values is thus shown with increasing bolt diameter. The largest mean shear stresses for $\varepsilon_l = 0.5\%$ and $e/D = 1$ lie at $\tau = 1.5$ to 2.5 kp/mm^2.

The shear strength of the material in comparison with the above were below these values, with $\tau_B = 1.5$ kp/mm^2.

It is apparent that the assumption for calculation that the shear stresses are restricted to the 0.4D plane is not always correct. Breaks by splitting occurred for all samples loaded to failure. Mean bolt hole strengths of $\sigma_L = 20$ kp/mm^2 were reached for large values e/D and $D = 10$ mm. In comparison with this, the compression strength of the material was approximately $\sigma_{dB} = 45$ kp/mm^2.

The maximum shear stresses at failure for samples with $e/D = 1$ and $D = 10$ mm amounted to $\tau = 2.5$ kp/mm^2.

Laminates with Reinforcements in ±45° Direction

The test values for the mean bolt hole stresses and shear stresses at the relative hole expansion of $\varepsilon_l = 0.5\%$ are plotted in Figure 3 as functions of e/D and D. The curves for the bolt hole compression stresses also show an asymptotic course and reach a limiting value at $e/D = 3$. These limiting values amounted to $\sigma_L = 9.0$; 11.2 and 16.0 kp/mm^2 for the diameter $D = 6$, 8 and 10 mm. The shear stresses had their greatest value with $\tau = 3$ at $e/D = 1$; 3.3 and 4.4 kp/mm^2 for $D = 6$, 8 and 10. There is thus shown a similar relationship to bolt diameter as for the 0° direction reinforced laminates.

The types of failure comprise split breaks at low values of e/D, and mainly bolt hole breaks at larger values of e/D, along with some tensile breaks at the sides for $D = 10$ mm.

The tensile breaks were limited to hole diameter $D = 10$ mm. The calculated mean tensile stress at the sides amounted to $\sigma_z = 13.3$ kp/mm^2 for a tensile strength of the material of $\sigma_{zB} = 14.3$ kp/mm^2. The stress peaks at the sides were apparently not very great. The ratio $s/D = 1.45$ thus represents a limiting value.

The bolt hole compression stress at break amounted to a maximum $\sigma_L = 25$ kp/mm^2 for $D = 10$ and $e/D = 5$. The compression stress of the material is $\sigma_{dB} = 16$ kp/mm^2. /913

The largest shear stress at failure amounted to $\tau = 8.8$ kp/mm^2 for a material shear strength of 0.4 kp/mm^2.

Laminates with the Reinforcements in 0 and ±45° Direction:

The mean bolt hole compression stresses and shear stresses at ε_l = 0.5% relative hole expansion are again plotted in Figure 4 in relation to e/D with D as parameter.

The bolt hole stresses again reach an asymptotic limiting value in relation to e/D as for the laminates discussed before. The asymptotic values of these curves are reached already at e/D = 2.2 and have the values σ_L = 10; 11.8 and 14.8 kp/mm^2 for D = 6, 8 and 10 mm. The mean shear stresses also plotted in Figure 4 are largest at e/D = 2 with τ = 3.8; 4.8 and 5.7 kp/mm^2 for D = 6, 8 and 10 mm.

The types of break were bolt hole shear breaks at low end spacing relationship e/D, while for larger values of e/D pure bolt hole breaks predominated. The outside plies failed just at the bolt hole shear breaks with the reinforcements in the ±45° direction with a bolt hole break, followed by the plies with the unidirectional (0°) fiber orientation by a shear break. The largest bolt hole strength was about 21 kp/mm^2 for the bolt diameter D = 10 mm. In comparison to this, the material compression strength is σ_{dB} = 33.5 kp/mm^2. The shear stresses at failure amounted to a maximum τ = 7.3 kp/mm^2 at e/D = 2. This value agrees completely with the measured material strength τ = 7.3 kp/mm^2 on the notched samples./

Comparison of the Bolt Hole Properties of the Laminates with the Various Fiber Orientations:

In Table 2 are shown the e/D values for which the limiting values of the bolt hole compression stresses were reached as function of e/D— which are also shown in the table. The limiting values of the bolt hole compression stresses at break are also shown in Table 2. For comparison, the compression strengths of the various fiber orientations are also shown in this table.

In Table 3 may be seen the maximum mean shear stresses for the relative hole expansion ε_l = 0.5% and at break, as well as the shear strength of the material and the types of break of the various reinforced laminates. The e/D values given in Table 2, at which the various samples reach the limiting values of the bolt hole compression stresses show a clear dependence on the fiber orientation.

TABLE 2. MEAN BOLT HOLE COMPRESSION STRESS VALUES OF KFK BOLTED JOINTS WITH 0°, ±45° AND 0° ± 45° FIBER ORIENTATIONS.

Fiber orientation	Linearity limits of the relative hole expansion ε_l (%)	Limiting value e/D at max. bolt hole compression stress for ε_l = 0.5%	Bolt hole compression stress at e/D limit for ε_l = 0.5% (kp/mm^2)			Bolt hole strength at e/D limit (kp/mm^2)			Compression strength of the material (kp/mm^2)
			D = 6 mm	8 mm	10 mm	D = 6 mm	8 mm	10 mm	[kp/mm²]
0°	0,5 to 0,7	3,2	7,1	9,2	10,8	15,1	13,9	17,1	45,6
± 45°	0,5 to 0,9	3	9,0	11,2	16,0	20,5	22,8	23,5	15,7
0 ± 45°	0,5 to 0,6	2,2	10	11,8	14,8	21	19,9	20,8	33,5

Note: Commas indicate decimal points.

TABLE 3. MEAN SHEAR STRESSES AND TYPES OF BREAKS OF KFK BOLTED JOINTS WITH 0°, ±45° AND 0° ± 45° FIBER ORIENTATIONS.

Fiber orientation	Mean shear stress (kp/mm^2) at e/D = 1 and ε_l = 0.5%			Shear stress at break (kp/mm^2) e/D = 1			Shear strength at failure for the material (kp/mm^2)	Type of break D = 6 mm e/D					Type of break D = 8 mm e/D					Type of break D = 10 mm e/D				
	D = 6 mm	8 mm	10 mm					1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
0°	1,5	2,5	2	1,6	2,5	2,5	1;5	SB	SB	SB	SB	SB	SB	SB	SB	SB	SB	SB	SB	SB	SB	SB
± 45°	3	3,3	4,4	7,9	6,8	8,8	9,4	SB	LL	LL	LL	LL	SB	LL	LL	LL	LL	SB	LL ZB	LL ZB	LL ZB	LL ZB
0 ± 45°	3,8	4,8	5,7	5 e/D = 2 7,3	4,9 4,3	6,1 6,2	7,3	LLS	LLS	LL	LL	LL	LLS	LL	LL	LL	LL	LLS	LL	LL	LL	LL

SB = split; LL - bolt hole break; ZB = tensile break at sides; LLS = bolt hole shear break.

Note: Commas indicate decimal points.

The ply material with the fiber reinforcement in 0° and ±45° direction, with ε_l = 0.5%, have already reached the limiting value of the bolt hole compression stresses at $e/D \approx 2.2$. The laminates with reinforcement in ±45°

direction reach the limiting value at $e/D \approx 3$, the unidirectional reinforced ply material at $e/D \approx 3.2$.

The limiting values of the bolt hole compression stresses of the ply material with reinforcements in 0° and ±45° direction are approximately the same as the corresponding values of the laminates with fiber orientation in ±45° direction. The unidirectional reinforced ply material in the 0° direction have their limiting values below these results. The bolt hole compression strengths behave similarly to the bolt hole compression stresses at 0.54, relative hole expansion.

The maximum mean shear stresses in Table 3 of the reinforced laminates in 0° and ±45° direction at $e/D = 1$ and $\varepsilon_l = 0.5\%$ are greater than the corresponding values of the ply material oriented in the ±45° direction. The samples with fiber orientations in ±45° direction show in contrast with this higher shear stresses at failure than the samples with fiber orientations in 0° and ±45° direction. In any case, the break measured values show very great scatter at $e/D = 1$.

Table 3 also shows by comparison the types of failure of the variously oriented laminates; they demonstrate particularly a clear cut dependence on the fiber orientation for small values of e/D.

With this it can be stated that laminates with reinforcement in 0° and ±45° direction are to be preferred for bolted joints, since relatively high bolt hole stresses are already reached at low e/D values.

Comparison of the Bolt Hole Behavior of Carbon Fiber and Boron Fiber Reinforced Plastics

Plastics reinforced with boron filaments (BFK) which were reinforced in 0° and ±45°, were also subjected to bolt hole experiments. They are described in detail in [3].

The samples had the same dimensions as for the carbon filament reinforced samples and were investigated under the same conditions. The load-hole expansion curves also were linear and had a linearity limit of $\varepsilon_l = 1.0\%$ /914 relative hole expansion. Figure 5 shows the values of the bolt hole compression stresses and shear stresses in relation to *e/D* and *D* as for the KFK laminates.

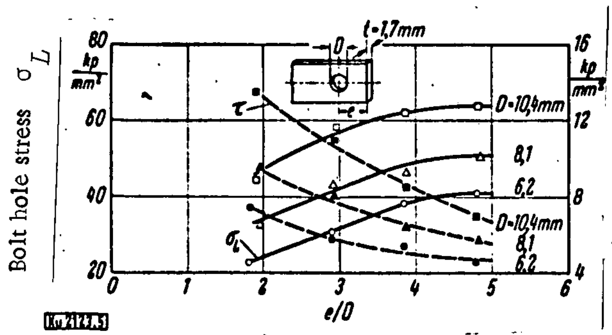

Figure 5. Mean Bolt Hole Compression Stress σ_L and Shear Stress τ of Bolted Joints in Boron Filament Reinforced Plastics (BFK) as a Function of *e/D* and *D* at the Relative Hole Expansion ε_l = 1.0%, Fiber Orientation 0° ± 45°.

The bolt hole stresses run similarly asymptotically as for the carbon filament reinforced plastics. The limiting values are about fourfold greater than those of the 0° and ±45° reinforced KFK.

The end spacing ratio *e/D*, at which the limiting values of the bolt hole are reached are about twice higher at *e/D* = 4.5 than those of KFK.

When the safe bolt hole stress of BFK and KFK are compared, referred to the weight and considering the various *e/D* limiting values, then 1.7-fold higher values are obtained for BFK than for KFK.

Adhesion has been used for a long time for bonding fiber reinforced plastics. Our own investigations on GFK adhesions were published in 1966 [4]. New investigations were necessary for adhesion bonding of plastics reinforced with boron fibers or carbon fibers. These investigations were to provide information as to which adhesives were suitable for these bonded materials, which factors affected the strength of a BFK adhesion, and practical possibilities for satisfactory strengthening of the above bonded material.

Boron fiber reinforced plastics were used for most of the investigations. However, in a few cases KFK were also tested for comparison. The laminate designation and data of manufacture have already been given in Table 1. The adhesive bondings were formed as overlapping adhesions. The adhesive was chosen from two points of view: the curing conditions during adhesion should influence the properties of the laminate as little as possible, and the adhesives should function as adhesive in aircraft construction. The chosen adhesives and the curing conditions are summarized in Table 4.

TABLE 4. ADHESIVES USED, DESIGNATIONS AND CONDITIONS OF TREATMENT.

Adhesive designation	Type of resin	Manufacturer	Ratio of mixing	Curing			Remarks
				Temp. (°C)	Time (hrs)	Pressure (kp/cm²)	
AF 126	Epoxid	3-M-Comp.	—	+ 120	1	2	Adhesive film
AT 1	Epoxid	Ciba	—	+ 130	14	1	
AW 134N+	Epoxid	Ciba	100 parts (wt)	+ 120	0,3	0,5	
HY 994	Polyaminoamid		40 parts (wt)	RT	24	0,5	
BSL 312	Epoxid	Ciba	—	+ 120	0,5	3,5	Adhesive film
Hidux 1197 A	Epoxid-Phenol	Ciba	—	+ 150	0,5	7	Adhesive film with glass cloth carrier
FM 123-5	Epoxid-Nitril	American Cyanamid Corp.	—	+ 120	0,25	2	Adhesive film with nylon cloth carrier
FM 1000	Epoxid-Nylon	American Cyanamid Corp.	—	+ 150	1	3	Adhesive film

Note: Commas indicate decimal points.

Bond Strength with Different Adhesives

Figure 6 surveys the bond strengths obtained for BFK and KFK adhesions with various adhesives. All adhesions did not break in the adhesive layer, but above the adhesive layer in the first ply of the laminated composition. This type of failure is customarily designated as "interlaminar strength." In spite of the same type of failure, the values of bond strengths are different for the various adhesives. This may be seen particularly clearly from Figure 7 in which the bond strengths of single notched Scotchply-BFK adhesions are plotted against the overlapping lengths for the adhesives FM 1000 and Hidux 1197 A. The highest stresses for an overlapping adhesion occur at the joint /915
and adhesive layer at the overlapping end. The joint is there stressed in tension and flexure, and the adhesive layer in shear and tension perpendicular to the direction of loading. The adhesive layer stresses attenuate to the middle of the overlap. The increase in stress at the end of the overlap is dependent on the dimensions of the joints, their elasticity characteristics and particularly on the shear and elasticity modulus of the adhesive.

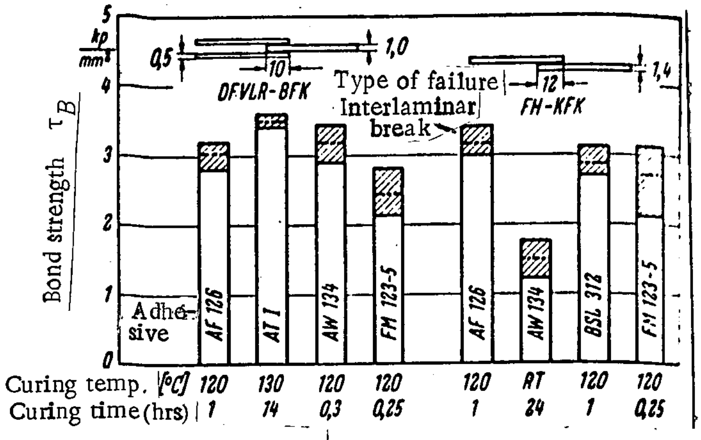

Figure 6. Bond Strength of BFK and KFK Adhesions for Various Adhesives. Interlaminar failure.

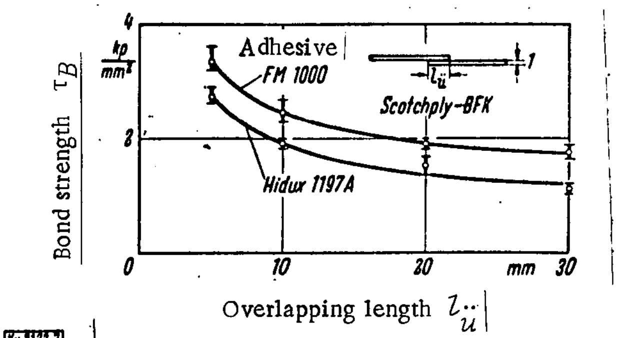

Figure 7. Bond Strength of BFK Adhesions, Adhesive FM 1000 (Epoxide-Nylon) and Hidux 1197 A (Epoxide-Phenol). Interlaminar failure.

The adhesive FM 1000 has a shear modulus which is about ten times smaller than for the adhesive Hidux 1197 A. In spite of this, the stress distribution in the adhesive layer is more uniform and the mean stress therefore higher.

One may assume that the stresses occur in the adhesive layer in a similar manner, also directly under the adhesive layer in the BFK laminate, and that the interlaminar break is started there by exceeding a certain limiting value. The evidence actually shows splitting of the BFK laminate at the overlapping end perpendicular to the fiber and loading direction.

The same rule thus is applicable for BFK adhesions as for the already known experience with metallic adhesions that the highest bonding strengths may be expected on bonding with adhesives of low modulus high intrinisic strength, and capacity for deformation. Besides, the bond strength is reduced with increasing overlapping length. The same thing should also be valid for KFK adhesions.

Bonding Strength at Increased Temperatures

For metal adhesions, the bonding strength under heat depends on the heat stability of the adhesive. In order to find out whether this is also the case for BFK adhesions, Scotchply laminate was bonded with the heat-stable adhesive Hudix 1197 A and tested at different temperatures. The bonding strengths obtained are reproduced in Figure 8. The bonding strength decreases with increasing temperature; again only interlaminar breaks were observed in the BFK. The comparison curve shown in Figure 8 for a metallic bonding without loss of strength shows clearly that the strength reduction of the tested BFK adhesions could be due only to the reduced interlaminar strength with increasing temperature.

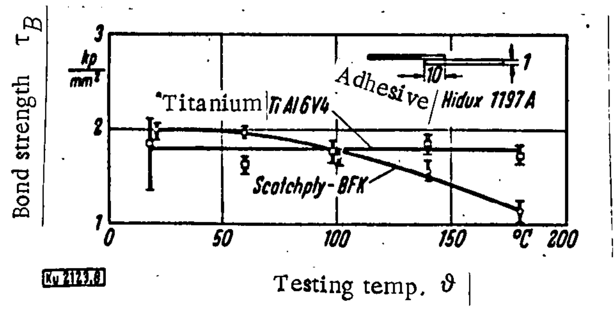

Figure 8. Bond Strength of BFK and Titanium Adhesions in Relation to Temperature. BFK adhesion: interlaminar failure; Titanium adhesion: failure in adhesive layer.

Therefore, for heat stressed adhesions of fiber reinforced plastics not only must the heat stability of the adhesive be considered but also that of the laminate.

Strength of BFK Adhesions with Other Metals

The experiments described heretofore gave the following difference compared to metallic bonding: The weakest point for metallic bonding is the adhesive; for BFK bonding it is the interlaminar strength of the BFK. Therefore both phenomena must be possible for bonding of BFK-metal.

Figure 9 shows a few results of experiments of tested adhesive bonds of BFK with stainless steel, aluminum alloy, and titanium. The two-notched compositions were at first so designed that the tensile stresses were equal in the joints. For short overlapping ($l_{ü}$ = 10 mm) the BFK-steel bond failed in the interlaminar region; the BFK-aluminum bond failed in the aluminum. When the overlapping length is increased ($l_{ü}$ = 20 mm), then the steel sheeting peels off from the adhesive layer perpendicular to the direction of loading due to its great plastic expansion, and the adhesive layer breaks. In a second series of experiments, the thickness of the metallic joints were increased. The expansions were thereby made smaller and the bonds again failed in the interlaminar region of the BFK. Single notched overlapping of BFK-titanium also showed interlaminar failure.

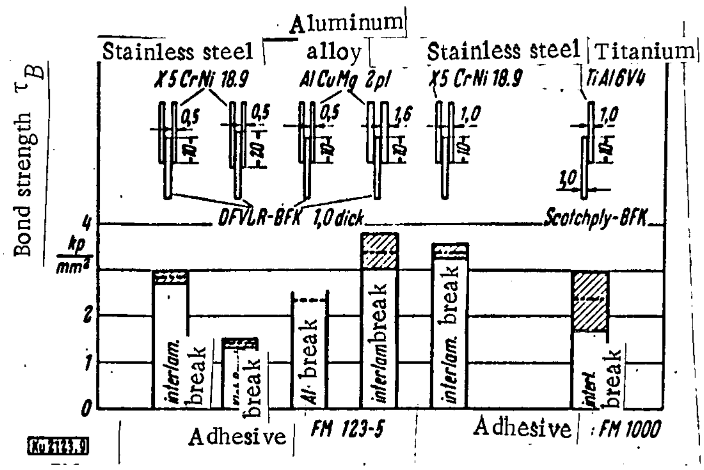

Figure 9. Bond Strength of Bonding BFK-Metal.

One can see from the experiments that adhesive layer failure may be expected in BFK-metal bonding when the metallic deformations arising during the loading are appreciably greater than the BFK deformations. In the other case, the interlaminar bond of the BFK is the weakest place of the bonding.

Interlaminar Strength

The interlaminar strength of fiber reinforced plastics is of the observed type of failure of BFK adhesions. A knowledge of it either makes possible the prediction of a failure for adhesion by comparison with the adhesive layer stresses to be expected, or it determines the practical design of a bonding. One differentiates between an interlaminar shear strength and an interlaminar tensile strength; the latter is generally designated as "transverse tensile strength." The determination of the transverse tensile strength does not occasion any difficulties since it is only necessary to carry out a simple tensile test perpendicular to the fiber orientation. The interlaminar shear strength on the other hand, can be determined in different ways. Menges and Kleinholz review the test methods [5] and recommend a supported, unsymmetrically notched flat bar, which permits a two-way stripping of the fibers in tensile loading. However, we used symmetrically notched flat bars for our own investigations, which were formed either by cementing two unsymmetrical bars, or for which the fiber positions were so laminated that a symmetrical "notched" tensile shear sample could be laminated in a sequence of operations. Symmetrically notched tensile shear samples behave like double overlapped bonding. The shear strength is dependent on the overlapping length. The shear strength is reduced with overlapping length; with decreasing overlapping length, the strength approximates the pure interlaminar shear strength. This strength value can be determined by torsion experiment with annular arrangement of surface elements. /916

The values for the interlaminar shear and tensile strengths are given in Figure 10. They were determined on tensile shear samples with the overlapping length $l_{\ddot{u}}$ = 10 mm. One recognizes that the shear and tensile strengths are dependent on the boron content. Both strengths are highest at about 65% (by volume) boron content; lower and higher boron contents reduce the strength. It may further be seen from Figure 10 that the interlaminar tensile is lower than the interlaminar shear strength. The difference varies with the BFK manufacture. The conclusion may therefore be drawn for the construction that adhesive bonding of fiber reinforced plastics must be so designed that tensile stresses are avoided, or should be kept as small as possible.

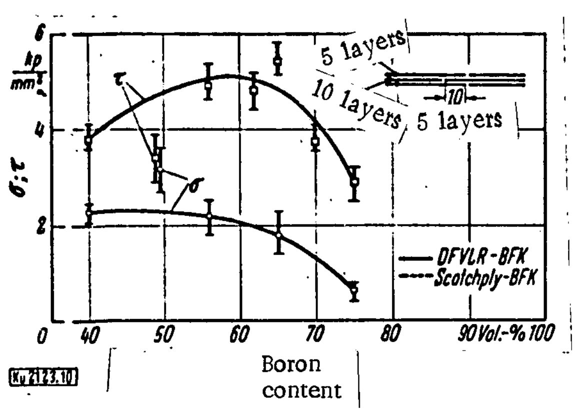

Figure 10. Interlaminar Tensile Strength σ and Shear Strength τ for BFK with Variable Boron Content.

Multilayer Adhesion

An example of the possibility of transmitting of force from BFK laminate to a steel construction by adhesion is the "multilayer adhesion" shown in Figure 11. In this type of bonding, the BFK prepregs on the one hand, and the steel sheeting on the other hand are so laminated that they overlap in a given region.

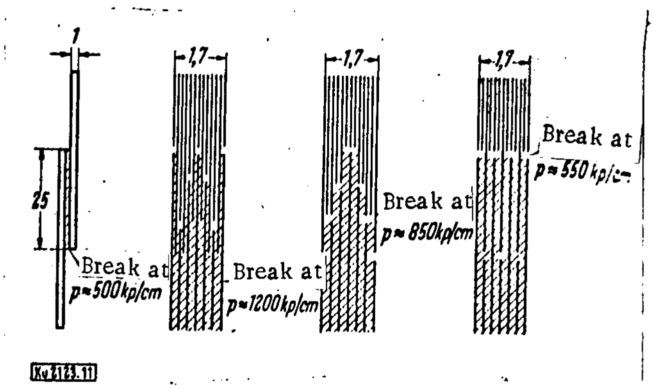

Figure 11. Multilayer Adhesion for BFK Steel Bonding (13 Layers Boron, Each 0.1 mm Thick, 7 Layers Steel, Each 0.1 mm + 6 Layers Adhesive); Examples and Comparison with Overlapping Adhesion.

A layer of adhesive is between the steel sheeting and in the overlapping region boron-steel. The layer set is pressed in the procedure and cured. A uniform force transmission from one material to the other is reached over the joint cross-section by the multilayer adhesion. Most boron layers are involved in the force transmission. Only one boron fiber layer is directly connected with the steel sheeting at the overlapping end, the point of normal stress maximum; an interlaminar tensile failure cannot occur. The loads at failure are therefore greater for such bonding than for the comparable overlapping adhesions.

The choice of design of steel sheeting and boron layers in the overlapping layer is dependent on the direction of orientation of the individual boron layers, i.e., which boron layers should assume the force transmitted. The steel, or BFK failure may be attained by clever design, as shown by experiment. The steel sheeting laminate itself can be attached to strengthening position either by cementing or by screws and rivets.

Summary

Bolt hole experiments were carried out on carbon fiber reinforced plastics (KFK) with the fiber orientation 0°, ±45°, as well as 0° and ±45° with different ratios of end spacing to bolt diameter e/D and bolt diameters D. The linearity limits of the load-hole expansion curves were determined which were a minimum of 0.5% for all fiber orientations.

The bolt hole stresses at this limit of deformation were plotted against e/D. The curves had an asymptotic course and reached their limiting values at $e/D \approx 3.2$; 3.0 and 2.2 for the orientations 0°, ±45° and 0° ± 45°. This

limiting value was dependent on the bolt diameter and fiber orientation. The bolt hole strength of the reinforced laminates in 0° and ±45° direction was about equal to the ±45° reinforced laminate. The values of the unidirectional laminates were somewhat lower.

There were always splitting breaks for the unidirectional KFK independent of e/D. For KFK oriented in ±45° and $e/D = 1$ there occurred splits, and for higher values of e/D mainly bolt hole failures along with a few side tensile breaks at $D = 10$ mm.

Laminates with 0° and ±45° fiber orientation fail at low e/D by bolt hole shear breaks and for high e/D by bolt hole breaks.

Laminates with fiber orientations in 0° and ±45° reach a relatively high bolt hole strength even with relatively small end spacing ratios e/D and should therefore be preferred for constructions.

Cementing is a suitable joining process for boron fiber reinforced plastics, in order to bond these materials with one another or with other metallic or nonmetallic materials. The experiments showed that the findings of metal cementing could be largely transferred to BFK cementing. A large number of practical adhesives are suitable for this purpose; deformable, high strength adhesives gave the highest bond strengths.

The interlaminar bond at the cementing position proved to be the weakest place of a BFK bonding. A screening of the interlaminar shear and tensile strengths yielded smaller strength values for tensile stress than for shear stress. The splitting of the BFK at the adhesive ends observed during the experiments could thus be explained.

Adhesive bonds with fiber reinforced plastics should therefore be so formed that normal forces perpendicular to the adhesive layer and laminate surface should be avoided if at all possible. It could be shown with an example of a multilayer cementing of BFK-steel that greater forces could thus be transmitted than with an overlapping adhesion.

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